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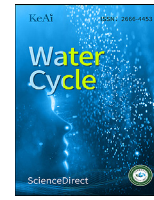

Water Eco-Nexus Cycle System (WaterEcoNet) as a key solution for water shortage and water environment problems in urban areas

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A R T I C L E I N F O

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A B S T R A C T

With the rapid socio-economic development, urban cities are confronted with issues of accelerating water scarcity, water contamination and water environment degradation. Optimizing water cycle in urban water systems becomes crucial towards the solving of the above-mentioned problems and the achievement of the sustainability goal. This study introduces a novel Water Eco-Nexus Cycle System (WaterEcoNet) that highlights the significance of reclaimed water (RW) in urban water cycle so as to enhance water ecosystem functions and public acceptance, reduce distribution costs, and strengthen regional water supplies. Through the WaterEcoNet model, the interlinks and interactions of multiple components of urban water systems can be well coordinated and embodied. Importantly, to ensure safe and long-term operation of WaterEcoNet, it is vital to apply both technical and management strategies for water allocation and fit-for-purpose use, water quality evaluation, monitoring, control, improvement and safety ensurance, etc. A case study in a county of China is further presented which illustrates the benefits of WaterEcoNet in enhancing regional water management. This study is of great theoretical significance and applicable value in promoting the effectiveness and sustainability of urban water systems.

1. Introduction

Faced with a fast-growing population and increasing water demands as well as highly variable climate and rainfall imbalances, many countries and regions in the world have experienced severe water shortage, increasing wastewater discharge and water contamination problems [1–4]. According to the report of UN Water, approximately one-fifth of the world's population (1.2 billion) live in areas of water scarcity and one-third of the world's population live in countries with moderate to high water stress [5]. Specifically, the city of Cape Town, South Africa is threatened to be the first city to run out of water with "Day Zero" crisis [6]. In China, by 2030, water availability will be reduced to 1800 m^3 per capita per year, leading to a gaping water shortage of 201 billion m^3 [7]. Overall, the global water demand continues to grow largely, which is estimated to increase by over 50% by 2050. This rapid growth further challenges water security for sustainable development [8].

Noticeably, the rapid socio-economic development is outpacing water carrying and supplying capacities in many water-stressed regions, especially in developing and emerging countries [8,9]. As a consequence, many places become difficult to ensure basic ecological flows, resulting in shrinkage of urban water bodies and water environment deterioration [10]. To cope with economic development and land use changes, some waterways (e.g. rivers, lakes and/or reservoirs) have been even diverted unwarrantedly for industrial and domestic applications. Even worse, in some places, the requirement to maintain minimum water flows in rivers, streams, and wetlands for water environment purposes become major challenges in urban water management [11]. On the other hand, approximately 80% of wastewater is released to the environment without adequate treatment and deterioration of water quality is found in many water bodies [5].

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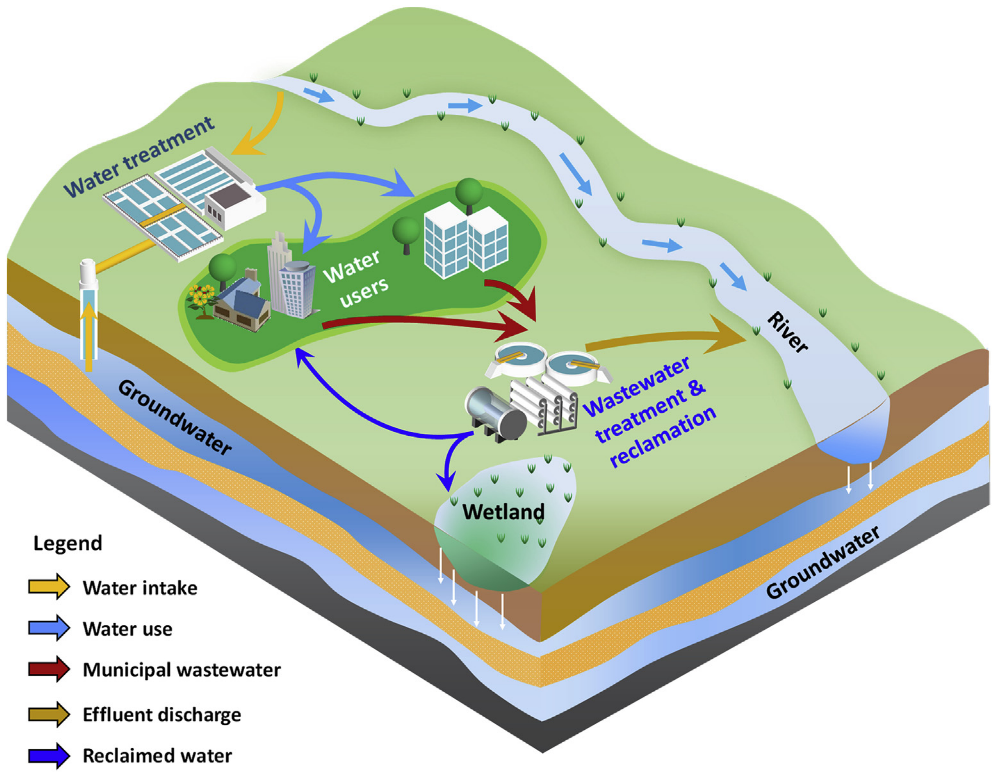

Fig. 1. The sketch and flow chart of a conventional urban water system.

These inevitably lead to impair or serious damage of water ecosystems in terms of eliminated wetlands, diverted water flows, over-exploitation of underground aquifers, salinization, hydrological alterations, etc. [12,13]. Water related issues are crucial for human health and the ecosystem. The linkages of water, health and ecosystems as well as social-ecological interdependencies, both on local and global scales, have gained increasingly attention. The impaired water ecosystems could accelerate water contamination issues, which aggravate water scarcity situation further, and thus threaten the long-term water security and sustainability [14]. The alternations also impact health vulnerability and risks to hazards that make up the majority of the global burden of disease [15].

Although the values of water ecosystems are less tangible, they are equally vital in environmental, health, social, economic and cultural realms and can offer versatile benefits [16–18]. Notably, because of ongoing urbanization, both urban surface flooding and heat island phenomenon are likely to be further aggravated since urban surfaces are continuously modified towards impervious. It is shown that water bodies can play important roles in urban heat island mitigation, especially during the night and evenings in summer seasons [19]. Urban waterways also help to alleviate flooding by strategies such as low-impact urban development, sustainable urban drainage system and water sensitive urban design [20].

Moreover, as an important natural element, water ecosystems are essential in urban green infrastructure development, landscape design and biodiversity. They are of great ornamental, recreational and ecological values owing to ecosystem protection, water quality improvement as well as public recognition and outreach [10,11,21]. In the context of urban water challenges, the need for a minimum ecological flow in rivers, streams and/or wetlands was highlighted in some cities. However, to what extent the quantity and quality of water ecosystems should be maintained still requires further research [22].

Having entered a new era where population growth and urbanization in some cities continue at accelerated paces, the sustainable management of urban water systems is key. This calls for not only technological improvements but also management strategies that can create more resilient and sustainable water systems to better meet society's future needs [23]. Current urban water supplies that rely mostly on excessive water extraction from surface and/or groundwater sources or water diversion from other regions are normally considered as unsustainable practices. Urban water management towards sustainable way that guarantees water supply capacity, water environment quality and socio-economic development has come to be an urgent need [24].

Remarkably, addressing water cycle in urban water systems is an effective way towards sustainability. This decreases the city's water requirement from outside, reduce its impact on water ecosystems and makes itself more resilient. Consequently, this study aims to identify possible constraints on current water systems and models in urban areas and present innovative solutions towards safe, smart and efficient water management.

2. Current urban water systems and the existing problems

A conventional urban water system generally involves the water intake in the upstream, water consumption by different sectors, wastewater discharge, treatment and reuse as well as partial effluent discharge to the downstream (Fig. 1).

In this approach, water flows are mainly monotonous and follow the once-through and single-use model [25]. Since different components (i.e. collection, supply, drainage and reuse) of the urban water system are separate and functioning individually, the interlinks and circuit could hardly be formed. Because of the unidirectional and single water supply model, it is also difficult to satisfy multiple end users with varied water quality requirements [7].

Nowadays, reclaimed water (RW) is increasingly being considered as an important way to alleviate multi-faceted water ecosystem challenges. It offers feasibility and reliability to restore dry and neglected urban streams, augment surface water for beneficial purposes as well as improve receiving water quality [26,27]. Therefore, as for water quantity, sufficient water sources for urban water systems can be guaranteed with continuous RW

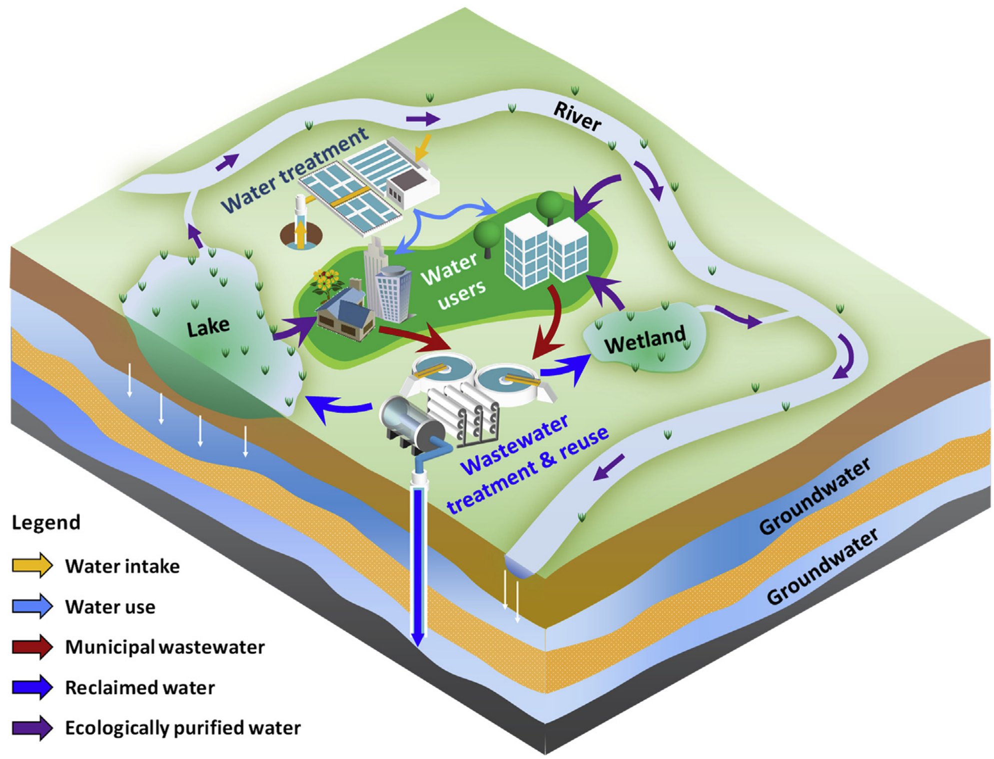

Fig. 2. The concept of Water Eco-Nexus Cycle System (WaterEcoNet).

supply. With respect to water quality, with ever stringent RW standard, water quality of receiving water bodies can be ensured as well. Presently, the RW quantity used for scenic environment enhancement has reached to 5.4 million m^3/day in the globe [28]. In China, the majority of RW are applied for environmental uses. For example, in Beijing, about 90% of RW are supplied for urban water ecosystems such as lakes, rivers and canals, which has greatly improved the urban landscape and ecological environment [29]. Likewise, in California, USA, nearly 25% of RW is used to replenish lakes. In Osaka, Japan, about 50% of RW is supplied for water feature improvement [10,11].

However, the following problems should be addressed when considering the long-term application of RW for environmental purposes. Firstly, in water-stressed situations, supplying RW for industrial, domestic and agricultural purposes has always been a high priority. It is often difficult to ensure constant RW supply for ecosystems under socio-economic constraints. In many places, a smaller quantity of RW was supplied to streams during peak season periods, which can lead to variations of the receiving water bodies [30]. As there is little connection and interaction of ecological water use with other water users for production and living, water use efficiency in current urban water systems is also relatively low [31,32].

Secondly, the effects on the quality of water bodies replenished by RW is quite different from that of surface water. RW, especially secondary effluent, normally contains higher amount of nutrients, organic matters and pathogens [33]. Studies that investigated impacts of RW on receiving water bodies are mainly limited to certain river stretches with monitoring of bulk water quality parameters [30]. In most instances, RW used for the purpose of ecological enhancement should meet or exceed local wastewater discharge standards. However, many existing standards for treated effluent discharge and water reuse only focus on bulk water quality parameters such as BOD, TSS, TN and TP. Other issues with respect to health safety, environmental safety and public acceptance of receiving water bodies have not yet been addressed seriously [34,35].

For instance, if chlorine is used for disinfection of treated effluent and reclaimed water, residual chlorine amount should be examined which may cause aquatic toxicity or form chlorinated byproducts capable of causing ecotoxicity [36,37]. Alongside the growing application of RW in streamflow augmentation, concerns have been raised as organic micropollutants are continuously introduced into the aquatic environment. Exposure to these accumulated trace and emerging pollutants are likely to induce health and ecological risks [38].

Thirdly, most urban water bodies are characterized as closed or semi-closed ecosystems with shallow depth, low flow rate, limited self-purification capability and low resilience to surrounding disturbances [39]. RW replenishment is an effective method to sustain urban water environment but it is still quite challenging to maintain the water quality and ensure ecological, ornamental and recreational functions in the long-term. It is shown that some water bodies replenished by RW were prone to eutrophication and water quality degradation because of combined effects of high nutrient levels, shallow depth, poor hydrodynamic condition, sunlight, etc. [40].

Fourthly, pathogens and resistance genes could be introduced to water bodies. It is demonstrated that the discharge of non-disinfected secondary treated effluent resulted in pathogenic concentrations exceeding background levels of rivers by several orders of magnitude. Despite of disinfection, the absence of indicator bacteria in RW does not necessarily indicate the absence of pathogens since some pathogens are more resistant to disinfectants. When the water is used in cascade for agriculture, elevated levels of pathogens might also be observed in irrigation water [30]. Notably, as ornamental and recreational uses (e.g. bird watching, fishing, boating and wading) can involve incidental or close contact of water features via inhalation, ingestion or dermal routes, microbial water quality are of concern for health safety issues [41,42].

Thus, it is crucial to analyze the key components in urban water systems, balance the demands of different water users and resolve the contradictions under social-economic and water environment context [43]. A greater focus has now been devoted onto urban water system optimization so as to move towards a sustainable, multifaceted, multi-level and multiscale development path [23,44–46].

Table 1
Aspects suggested to be considered in design and planning of WaterEcoNet.

Aspects	Indicators
Economic aspect	Costs on construction and operation
Environmental impact	Effects on water environment improvement
	Quantity of water supply
Technical feasibility	Degree of system complexity
	Degree of supply-demand matching
	Difficulty in management and operation
Social aspect	Effects on ecology and landscape
	Public acceptability

3. Water Eco-Nexus Cycle System (WaterEcoNet)

To improve sustainable water management in urban water systems, enhancing water cycle is considered to be an efficient way to enhance water supply capacity, increase water use efficiency and improve water environment quality [18,21,47–51]. Moreover, the sustainable development goals by United Nations (UN SDG-6) further highlight the substantial increase of safe water reuse globally and implement integrated water resources management at all levels by 2030 [52]. Consequently, a new Water Eco-Nexus Cycle System (WaterEcoNet) has been proposed. It aims to establish a safe and smart urban water system to enhance water quality, maximize water use efficiency while maintain ecological, ornamental and recreational functions simultaneously. The concept, characteristics and technological measures of WaterEcoNet are explained in detail.

3.1. The concept

As can be seen from Fig. 2, the newly proposed WaterEcoNet model generally follows a water cycle of "urban water use−wastewater drainage−water reclamation and reuse− urban water ecosystem supplement−urban water use". The WaterEcoNet has transformed conventional urban water systems into innovative and distributed treatment which relies on distributed facilities rather than large scale centralized systems for water ecosystems.

It highlights the use of RW for water environment restoration and/or enlargement, such as river, lake or wetland, while simultaneously storing and purifying water. Afterwards, cascading use can be implemented and the ecologically purified water will be applied for industrial, domestic and agricultural uses to form an integral WaterEcoNet in urban areas. Meanwhile, correlation and interaction among different water use applications are encompassed. The concept of WaterEcoNet model fully supports the UN SDG-6 on clean water and sanitation [24].

3.2. The characteristics

The WaterEcoNet model has turned the previous end user of RW, namely the urban water bodies, into "new water resources". Apart from satisfying ecological functions, a proportion of urban streams receiving constant RW supply can be further extracted for subsequent industrial, domestic and/or agricultural uses. Hence, the receiving water bodies can also be regarded as a new starting point for cascading use of RW. This helps to achieve fit-for-purpose water reuse and optimize water resource allocation. In addition, substantial costs on water pipeline construction and distribution can be reduced by using water ecosystems as a means of water storage, transmission and conveyance.

Moreover, WaterEcoNet is able to solve the growing competition between water requirements for production and living and water for ecosystems in burgeoning cities and ever-expanding industrial developments. As such, with the strengthened water cycle, water use efficiency can be maximized and the resilience of urban water supply can be largely enhanced. Besides, the receiving water bodies can promote natural properties of RW, enhance public acceptability and act as environmental buffers for RW storage, adjustment and purification. After that, public awareness, engagement and motivation on water reuse are likely to be largely elevated.

3.3. Key technical guarantee approaches and requirements

As for WaterEcoNet planning, it is crucial to convert the conventional design concept from centralized wastewater treatment into distributed treatment, and consider the RW from distributed facilities as a vital resource for water ecosystems. As such, water ecosystems can be significant components for water transmission and distribution, water storage, purification and water quality enhancement. The links/compliance of WaterEcoNet with local or regional water planning should also be addressed. The selection of optimal options for RW replenishment (e.g. facility location, recharge quantity, quality and frequency), should consider versatile aspects though a multiple criteria analysis (Table 1).

Afterwards, it is essential to establish a hierarchical structure for water resource allocation to manage and coordinate miscellaneous water users regarding their specific demands on water quality, quantity, peak use period and spatial location as well as cascading uses. The overall target of WaterEcoNet is to achieve RW supply-demand balance, fit-for-purpose and multiple utilization, reduce water transmission and distribution costs while maximize regional water supply benefits. Compared to conventional urban water use systems, WaterEcoNet generally involves less complexity in system design, planning and management, but can better balance water supply and demand at spatial and temporal scale.

Regarding to WaterEcoNet construction, a key aspect is to determine the scale, layout, influent quality and treatment requirements of the wastewater treatment plant (WWTP) as well as the geographical distributions of users. Key technologies need to be performed including constructed wetland (CW) construction (e.g. wetland type such as subsurface or surface flow CW, water depth, plant type and hydraulic retention time), algal bloom control, operational management, and overall system evaluation.

Considerations and analyses on water quality and quantity requirements are paramount to facilitate fit-for-purpose water applications. In regard to water quality effects, aesthetic effects mainly refer to aesthetic perception caused by transparency, color, odor, turbidity, etc. Ecological effects are mainly associated with toxicity and adverse impacts on biological functions triggered by heavy metals, toxic and harmful organic pollutants, algal toxins, etc. Comparatively, health effects mainly refer to impacts induced by chemicals and pathogenic microorganisms [11].

For improvement and long-term maintenance of water quality in WaterEcoNet, it is important to analyze the RW quality prior to supplement, urban water quality variations during RW hydraulic retention time and further extraction [10]. Some site-specific issues such as degree of RW mixing and dilution, upstream load, in-stream attenuation processes need to be considered as well [7,39,53]. Systematic assessment is needed to identify situations where acceptable environmental and health risk levels are exceeded and mitigation strategies are warranted [30].

Importantly, the development and implementation of relevant standards and regulations become imperative to ensure safe practices. Using RW meeting approved standards can better guarantee the water safety associated with the potential presence of chemical and microbial contaminants in RW [30,37]. Apart from routine physical and chemical parameters, other parameters related to aesthetic, ecological and health effects should be emphasized. Accordingly, comprehensive water quality detection and evaluation methods are suggested to be established. Appropriate evaluation indicators should be specified as well [35,54].

Noticeably, existing detection methods for trace organic compounds (e.g. EDCs, antibiotics and algal toxin), biological stability and microbial indicators are considered to be tedious, costly and time-consuming, which call for rapid detection techniques and tools [55,56]. Additionally, technical and/or legislative proposals of minimum quality requirements for RW in WaterEcoNet can be developed.

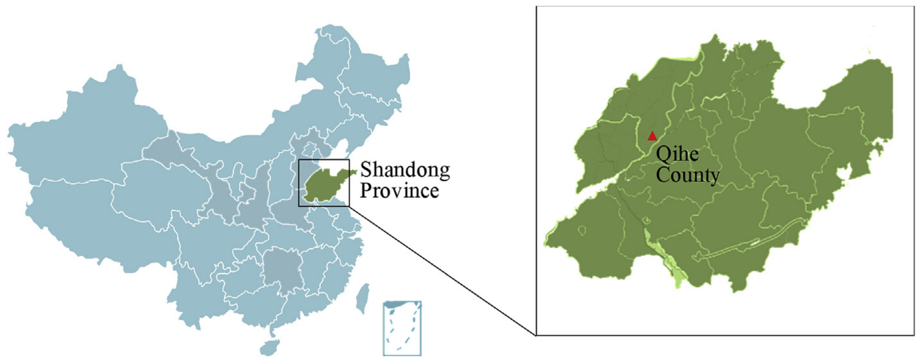

Fig. 3. Location of the WaterEcoNet demonstration projects in Qihe County, China.

Table 2
The main projects in the WaterEcoNet of Qihe.

WaterEcoNet model	Treatment process	Treatment capacity (m^3/d)	Water quality (mg/L)	
			COD_{Cr}	NH_3–N
WRP	Carrousel oxidation ditch	20,000	50	5
CW1	subsurface flow CW	2000	30	1.5
CW2	surface flow CW	20,000	40	2

The success of WaterEcoNet model in providing safe and enjoyable environmental and recreational opportunities depends largely on long-lasting maintenance and control of water quality. A multiple barrier approach and other management strategies can be adopted to mitigate potential risks of a variety of contaminants [37]. The multiple barriers of WaterEcoNet generally consist of source control, wastewater treatment, advanced water treatment, disinfection, ecosystem recharge and buffer, and additional control for cascading water uses. Each of the process can remove multiple classes of microbial and/or chemical contaminants to some extent and helps in producing high-quality RW for environmental and recreational uses [57].

For instance, a source control program is capable of reducing risks from non-point source discharge of detergents, salts, defrosting agents and other chemicals to urban streams [35]. The selection and sequence of multiple barriers for WaterEcoNet needs to consider RW quality, regulatory requirements, synergetic effects of different treatment processes, characteristics of the ecosystems (e.g. ecological reserves, properties and hydrodynamic conditions), as well as cost and energy aspects. Besides, a monitoring program characterized by high sampling frequencies and a comprehensive microbial screening can be in place. The monitoring programs such as online monitoring, alarms and automatic controls can detect and control treatment process failures, illegal discharges as well as security issues in urban water ecosystems [35,58].

4. The case study

Faced with a myriad of urban water challenges, one WaterEcoNet project in China is illustrated to verify its effectiveness as a sustainable approach for future urban areas. The WaterEcoNet model was built in Qihe County of China, to solve local water shortage and water environment problems caused by the rapid development of economy and society. Particularly, Qihe County is in the southeast of Shandong Province (Fig. 3). Until 2017, the population of Qihe was 0.63 million and the GDP was 46.9 billion RMB. The water consumption per ten thousand GDP of Qihe was 94.78 m^3.

As shown in Table 2, Figs. 4 and 5, the WaterEcoNet model in Qihe consists of a water reclamation plant (WRP, 20,000 m^3/d), a subsurface flow CW (2000 m^3/d) and a surface flow CW (40,000 m^3/d). Part of RW is reused by chemical and paper industry (10,000 m^3/d). Part of the RW is further purified by the subsurface flow CW and then reused as environmental water supplement for Yanhuang river. The surface flow CW is built at the junction of Yanhuang river and Zhaoniu river. The water in two rivers was reused as domestic miscellaneous water and also reused by the farmers along the river course as irrigation water. The effluent from the WRP can stably meet the Class A level specified by national discharge standard of pollutants for municipal WWTP (GB 18918-2002) with $COD_{Cr}<50$ mg/L, SS $<$ 10 mg/L, TN $<$ 15 mg/L, NH_3–N<5 mg/L and TP $<$ 0.5 mg/L, respectively. After the sequential constructed wetlands, the effluent quality can meet the Class IV level of national environmental quality standards for surface water (GB 3838-2002) with $COD_{Cr}<30$ mg/L, TN $<$ 1.5 mg/L, NH_3–N<1.5 mg/L and TP $<$ 0.1 mg/L, respectively.

The WaterEcoNet project in Qihe is now operating in good conditions, which provides a cozy water environment for public ornamental and recreational activities. The rivers and wetlands attract many local residents for visit, entertainment and education. Particularly, the WaterEcoNet significantly decreased the freshwater demand and pollution discharge in Qihe County. Freshwater usage in the area was decreased by 25 million m^3/year and the discharge of COD_{Cr} and ammonia were decreased by 3421 and 403 tonnes/year, respectively.

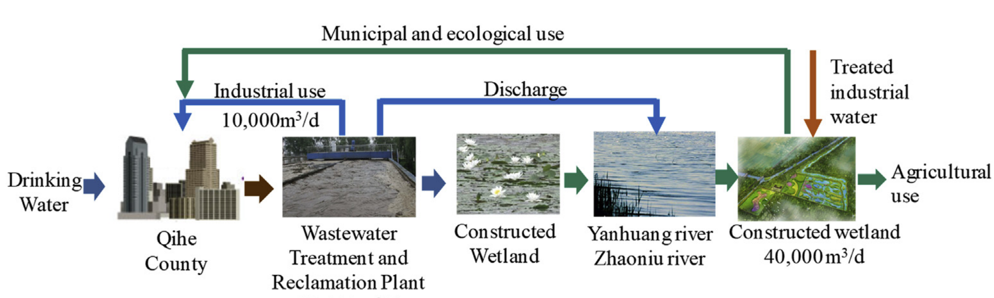

Fig. 4. Schematic flows of the WaterEcoNet project in Qihe County, China.

Fig. 5. Layout of the WaterEcoNet project in Qihe County, China.

In China, WaterEcoNet has become a recommended new model in several national guidelines and regulations for urban water management [59,60]. According to the National Action Plan for Prevention and Control of Water Pollution, by 2020, water reuse rate in water deficient areas should reach to 20% while in Beijing-Tianjin-Hebei region, the figure should be higher than 30% [60]. Therefore, there is great room for development and expansion of WaterEcoNet in the future. Currently, WaterEcoNet projects are planned and successfully implemented in over 15 provinces of China.

5. Summary and future development

Water cycle of urban water systems is an effective way to improve resiliency and sustainability of urban cities. This study proposes a novel WaterEcoNet model that follows a water cycle of "urban water use−wastewater drainage−water reclamation and reuse− urban water ecosystem supplement−urban water use". The WaterEcoNet aims to establish a safe and smart water system which can achieve maximized water savings, ecological restoration and water environment creation while minimizing wastewater discharge and distribution costs. It is believed that WaterEcoNet is a sustainable system for future urban areas. The study also highlights the implementation of both technical and management approaches such as strategies for water allocation and fit-for-purpose use, indicators and detection methods for water quality evaluation, multiple barrier approach for mitigating potential ecological and health risks, and standard and policy formulation, so as to ensure safe and long-term operation of WaterEcoNet models. This new strategy can be considered for more case studies across the globe.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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